

# First evidence of a cyclotron feature in an anomalous X-ray pulsar

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We report on the results of the longest uninterrupted observation of the Anomalous X-ray Pulsar 1RXS J170849–400910 obtained with the *BeppoSAX* satellite in August 2001. The best fit phase-averaged spectrum was found to be an absorbed power law plus blackbody model, with photon index  $\Gamma \sim 2.4$  and a black body temperature of  $kT_{bb} \sim 0.4$  keV. We confirm the presence of significant spectral variations with the rotational phase of the pulsar. In the spectrum corresponding to the rising part of the pulse we found an absorption-like feature at  $\sim 8.1$  keV (significance level of  $4\sigma$ ), most likely due to cyclotron resonant scattering. The centroid energy converts to a magnetic field of  $9 \times 10^{11}$  G and  $1.6 \times 10^{15}$  G in the case of electrons and protons, respectively. If confirmed, this would be the first detection of a cyclotron feature in the spectrum of an anomalous X-ray pulsar.

## 1. Introduction

Anomalous X-ray pulsars (AXPs) are characterized by spin periods in the range of 5–12 s, steady spin down ( $\sim 10^{-11} \text{ ss}^{-1}$ ), steep and soft X-ray spectra with luminosities exceeding by several orders of magnitude their spin-down luminosities (Mereghetti & Stella 1995). All five confirmed AXPs lie in the “galactic” plane and two (or three), are associated with supernova remnants. AXPs show no evidence for a companion and are thus believed to be isolated neutron stars either having extremely strong magnetic dipole fields ( $\sim 10^{14} - 10^{15}$  G; “magnetars”; Duncan & Thompson 1992) or accreting from a residual disk (Alpar 2001). For recent reviews see Mereghetti et al. 2002, and references therein.

1RXS J170849–400910 was discovered with ROSAT (Voges et al. 1996) and  $\sim 11$  s pulsations were found in its X-ray flux with ASCA (Sugizaki et al. 1997). This source presents a strange timing behaviour, it is a quite stable rotator except few glitch type events that occurred in its secular spin-down (Kaspi et al. 2000, Dall’Osso et al. 2003, Kaspi & Gavril 2003). Searches for an optical counterpart ruled out the presence of

a massive companion (Israel et al. 1999); an IR counterpart has been recently proposed (Israel et al. 2003). There is no evidence of pulsed radio emission from the AXP with an upper limit of  $70 \mu\text{Jy}$  on the pulsation amplitude (Israel et al. 2002).

Here we report on the longest observation (200.0 ks) of this source, made with *BeppoSAX* in August 2001. Analysing spectral data we discovered the first absorption-like feature ever seen in an AXP, probably due to cyclotron resonant scattering. For more details about the observation and the analysis see Rea et al. 2003.

## 2. Timing and spectral results

The timing analysis allowed us to estimate a spin period of  $11.000563 \pm 0.000005$  s. The source shows an energy-dependent profile (Fig. 3), in particular the pulse minimum shifts from a phase of  $\sim 0.0$  in the lowest energy light curve (0.1–2 keV) to  $\sim 0.3$  in the 6–10 keV light curve. Correspondingly, the pulsed fraction decreases from  $\sim 30\%$  to  $\sim 17\%$ .

The energy spectra were well fit with an absorbed blackbody plus a power law model. The best fit of the phase-average spectrum gave a reduced  $\chi^2$  of 0.95 for 298 degree of freedom (dof)

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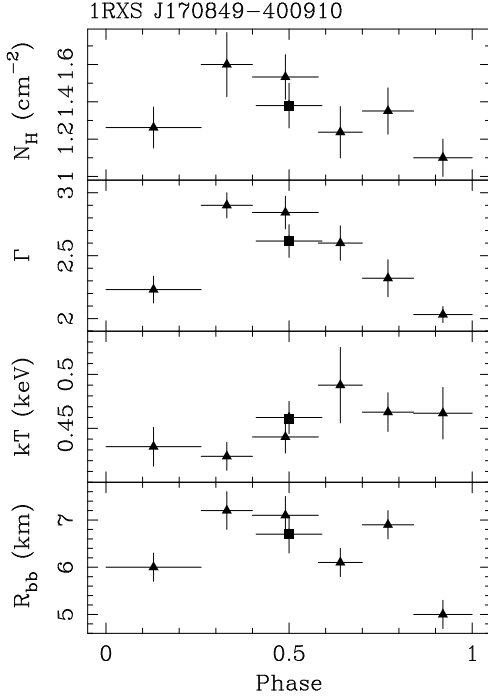


Figure 1. Spectral parameters variability with phase, using an absorbed black body plus power-law model. Filled squares represent the spectral parameters after the addition of a cyclotron line model in the 0.4 – 0.58 phase interval. Note that the relevant points are slightly shifted in phase for clarity.

for the following parameters: column density of  $N_H = (1.36 \pm 0.06) \times 10^{22} \text{ cm}^{-2}$ , a blackbody temperature of  $kT_{bb} = 0.44 \pm 0.01 \text{ keV}$  (blackbody radius of  $R_{bb} = 6.6 \pm 0.4 \text{ km}$ , assuming a distance of 5 kpc) and a photon index of  $\Gamma = 2.40 \pm 0.06$  (all error bars in the text are 90% confidence). The unabsorbed flux in the 0.5–10 keV range was  $1.87 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$  corresponding to a luminosity of  $5.6 \times 10^{35} \text{ erg s}^{-1}$  (for a 5 kpc distance). In the 0.5–10 keV band the blackbody component accounts for  $\sim 30\%$  of the total unabsorbed flux (see Fig. 2).

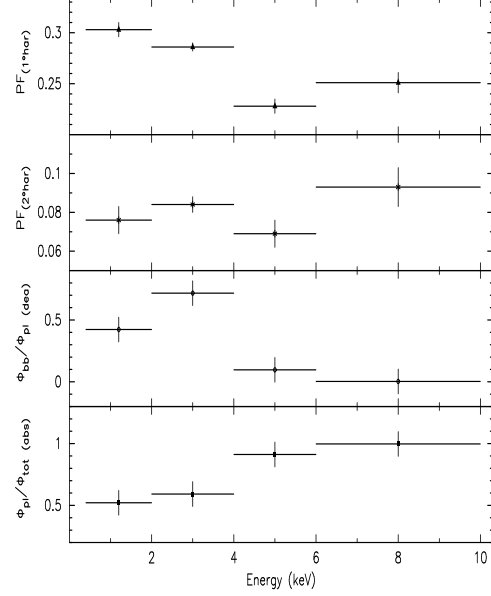


Figure 2. The first two panels show the pulsed fractions of the first and the second harmonics of the spin period in function of energy. In the third panel is presented the relative intensity of the fluxes of the power-law and the black body components and in the last one, of the power-law and the total flux, all in function of energy.

In order to search for spectral features we made a pulse phase spectroscopy and accumulate spectra in six different phase intervals (see Fig. 1 and Tab. 1). A significant variation of the spectral parameters with pulse phase was clearly detected (especially for  $\Gamma$ ) and confirm what previously reported in literature (Israel et al. 2001). In all intervals but one, an acceptable fit was obtained with the absorbed power-law plus black body model (reduced  $\chi^2$  in the 0.9–1.1 range); a reduced  $\chi^2$  of 1.2 was instead obtained in the 0.4–0.58 phase interval. In the latter case, the data were systematically below the best fit model in the  $\sim 7.8$ – $8.4 \text{ keV}$  range (see Fig. 4b).

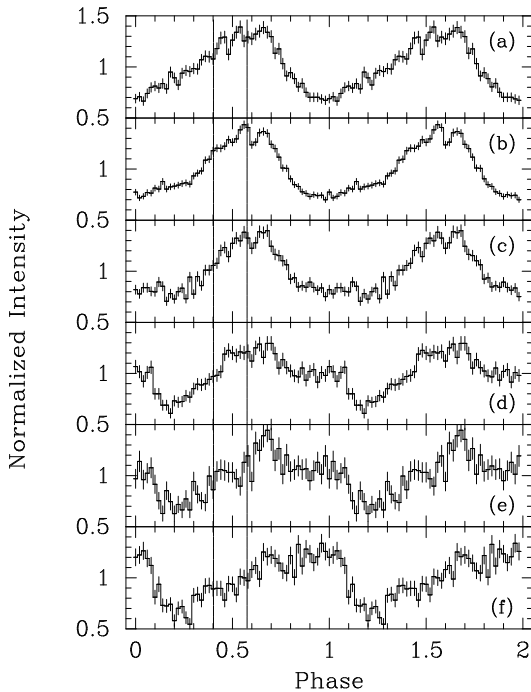


Figure 3. MECS light curves of 1RXSJ170849–400910 folded at the best spin period (two pulse cycles are shown) for six energy bands: (a) 0.1–2 keV; (b) 2–3 keV; (c) 3–4 keV; (d) 4–5 keV; (e) 5–6 keV; (f) 6–10 keV. The vertical lines mark the phase interval in which the absorption-like feature was detected.

We tried to fit three different models: a Gaussian, an absorption edge and a cyclotron feature.

While the inclusion of a Gaussian or an absorption edge did not lead to a significant improvement of the fit, the cyclotron model (CYCLABS in the XSPEC package, see Mihara et al. 1990 for details) led to a reduced  $\chi^2$  of 1.09, corresponding to an F-test probability of  $1.8 \times 10^{-5}$  implying to a single trial significance of  $4.5\sigma$  or  $4\sigma$  after correction for the six spectra that we analysed (see Fig. 4 and Tab 1). Moreover, taking into account also the possibility of find the feature in all 1-10 keV range, we found a  $3.5\sigma$  confidence level.

### 3. Discussion

During the analysis of the longest *BeppoSAX* observation of 1RXSJ170849–400910 we discovered an absorption-like feature at an energy of  $\sim 8.1$  keV in a pulse phase interval corresponding to the rising part of the  $\sim 11$  s pulse. This feature was best fit by a resonant cyclotron feature model with a centroid energy of  $\sim 8.1$  keV and an equivalent width of  $\sim 460$  eV (see Fig. 4 and Tab. 1).

The detection of an RCF in a specific pulse-phase interval and superposed to an X-ray continuum that varies with the pulse phase is reminiscent of the behaviour seen in standard accreting pulsars in X-ray binaries (Wheaton et al. 1979). If interpreted as an electron resonant feature at the base of the accretion column, the feature at  $\sim 8.1$  keV implies a neutron star surface magnetic field of  $\sim 9.2 \times 10^{11}$  Gauss (using a gravitational redshift  $z=0.3$ ). This value is just slightly lower than that measured for electron RCFs in typical accreting X-ray pulsars (see Fig. 5); more interestingly it is close to that required by models for AXPs which involve residual disk accretion in the spin-down regime. In this context, one can solve the torque equation (see e.g. Eq. 11.35 in Henrichs 1983) by exploiting the measured value of  $\dot{P}$  and range of accretion luminosity derived from plausible distances (5–10 kpc). The surface magnetic (dipole) field obtained in this way is  $0.6$ – $1.1 \times 10^{12}$  G (corresponding to a fastness parameter range of  $\omega_s = 0.57 - 0.54$ , a typical value for the spin-down accretion regime; see Ghosh & Lamb 1979 and Henrichs 1983).

The agreement of this estimate with the magnetic field inferred from the electron RCF inter-

pretation is intriguing, especially in consideration of the other analogies with the pulse-phase spectral dependence of conventional accreting X-ray pulsars. By contrast, if an electron RCF arose somehow at the polar caps of a rotation powered pulsar, a B-field strength of  $9.2 \times 10^{11}$  G would be in the range of many radio pulsars and yet much lower than that required to spin-down at the observed rate through magnetic dipole radiation ( $\sim 5 \times 10^{14}$  G, indeed this was one of the motivations for magnetar model, see below).

There is a clear correlation between the width and centroid energy of the electron RCFs in accreting X-ray pulsars (see Fig. 5, extending the results of Orlandini & Dal Fiume 2001). The values from 1RXS J170849–400910 and SGR 1806–20 are in good agreement with such a relation. The modest range of width to centroid energy ratio implied by this indicates that magnetic field geometry effects at the neutron star surface likely dominate the RCF width (on the contrary temperature and particle mass would alter this ratio). This, in turn, suggests that similar (relative) ranges of surface magnetic field strength are “sampled” by RCFs in accreting X-ray pulsar and, by extension, RCFs in AXPs and SGRs.

Alternatively the RCF might be due to protons. For the magnetic field strengths foreseen in the “magnetar” scenario, proton cyclotron features (if any) are expected to lie in the classical X-ray band (0.1–10 keV; Zane et al. 2001; Lai & Ho 2002). A proton RCF feature at  $\sim 8.1$  keV would correspond to surface field of  $1.6 \times 10^{15}$  G ( $z=0.3$ ). The fact that this value is  $\sim 3$  times higher than the surface field derived from the usual magnetic dipole spin-down formula should not be of concern. According to the magnetar model, the magnetic field at the star surface and its vicinity is dominated by higher order multipole field components. At large radii the dipole component, responsible for the secular spin-down, dominates. It is thus expected that a proton RCF feature, sampling the (total) surface magnetic field strength, provides a higher value than the mere dipole component.

Other interpretations of the feature at  $\sim 8.1$  keV appear less likely. Firstly, fitting an edge or line due to photo-electric absorption provides

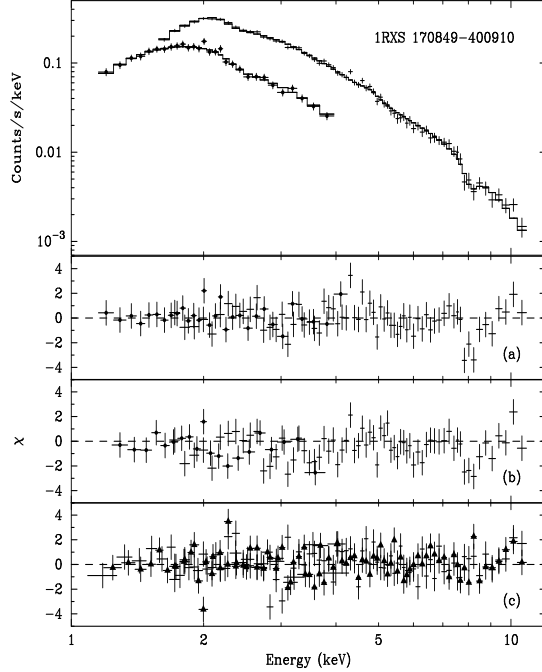


Figure 4. MECS and LECS spectra from the 0.4–0.58 phase interval fit with the “standard model” (the sum of a blackbody and power law with absorption) plus a cyclotron line. Residuals are relative to the “standard model” alone in order to emphasize the absorption-like feature at  $\sim 8.1$  keV: (a) the *BeppoSAX* observations merged together; (b) the 2001 observation alone; (c) the phase intervals contiguous to that showing the cyclotron absorption feature in the merged observations.

a less pronounced improvement of the fit than the RCF model. Secondly, an edge by iron at a

Table 1  
Spectral parameter values of the phase resolved spectroscopy

Phase	0.0–0.26	0.26–0.4	0.4–0.58	0.58–0.7	0.7–0.84	0.84 – 1.0
$N_H (\times 10^{22} \text{ cm}^{-2})$	$1.26 \pm 0.11$	$1.6 \pm 0.1$	$1.38 \pm 0.12$	$1.24 \pm 0.14$	$1.35 \pm 0.12$	$1.1 \pm 0.1$
$\Gamma$	$2.2 \pm 0.1$	$2.9 \pm 0.1$	$2.62 \pm 0.13$	$2.60 \pm 0.13$	$2.30 \pm 0.15$	$2.03 \pm 0.06$
$kT_{bb}$ (keV)	$0.433 \pm 0.017$	$0.424 \pm 0.013$	$0.46 \pm 0.01$	$0.49 \pm 0.03$	$0.465 \pm 0.018$	$0.46 \pm 0.02$
$R_{bb}$ (d = 5 kpc; km)	$6.0 \pm 0.3$	$7.2 \pm 0.4$	$6.7 \pm 0.4$	$6.1 \pm 0.3$	$6.9 \pm 0.3$	$5.0 \pm 0.3$
$E_{cyclabs}$ (keV)	–	–	$8.1 \pm 0.1$	–	–	–
Line Width (keV)	–	–	$0.2 \pm 0.1$	–	–	–
Line Depth (keV)	–	–	$0.8 \pm 0.4$	–	–	–
$\chi^2/d.o.f.$	1.08	0.98	1.09	0.99	1.09	1.05

sufficiently large distance from the neutron star that energy shifts are negligible would require a high overabundance of this element and intermediate ionisation stages (such as C-like iron). Yet it has long been known that the photoionisation equilibrium of such a plasma is unstable (Krolik & Kallman 1984; Nagase 1989). The energy of an ion feature forming in the neutron star atmosphere would be drastically altered by magnetic field effects (see Mori & Hailey 2002 and references therein). In this and the above interpretations, however, it would also be difficult to explain why an ion feature is observed only over a restricted range of pulse phases.

#### 4. Conclusion

In conclusion, we found an absorption-like feature in the *BeppoSAX* X-ray spectrum of 1RXSJ170849–400910 taken during the rising phase of the  $\sim 11$ s pulse, which is best fit by a cyclotron resonant scattering model. If this interpretation is correct, the centroid energy translates into a model-independent magnetic field strength of  $\sim 1.6 \times 10^{15}$  G or  $\sim 9.2 \times 10^{11}$  G depending on whether protons or electrons, respectively, are responsible for the feature.

Further observations and polarization measurements might choose between the two case. If the line is due to protons this result will give the confirmation that AXPs are magnetars, if instead, is due to electrons, this depress the magnetar model in favor of accretion-driven models for analogy with other accreting pulsar magnetic field strengths known so far.

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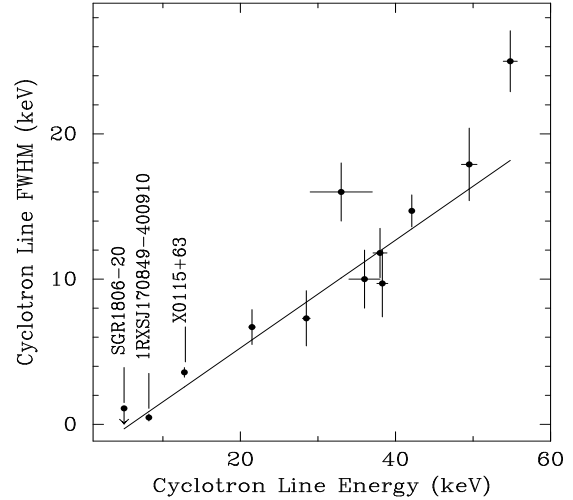


Figure 5. Line width vs. centroid energy from a sample of accreting X-ray pulsars with electron RCFs (Orlandini & Dal Fiume 2001), 1RXSJ170849–400910 (this Letter) and SGR 1806–20 (Ibrahim et al. 2002).